LOW CURRENT
MEASUREMENTS

APPLICATIONS OVERVIEW

MODEL 428 CURRENT AMPLIFIER

MODEL 486 PICOAMMETER

MODEL 487 PICOAMMETER/SOURCE

KEITHLEY INSTRUMENTS

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INTRODUCTION

This booklet is a collection of applications for the Keithley Models 428 Current Amplifier, 486 Picoammeter, and 487 Picoammeter/Voltage Source. It was compiled to present ideas about using these new low current intruments in your test applications. These units can provide very efficient solutions for fast, low current measurements.

If you would like complete specifications on these products, please consult the technical brochure. If you have specific questions or a particular test design issue, call our Applications Department.

1-800-552-1115 (U.S. only)

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CAPACITOR LEAKAGE MEASUREMENTS

Overview

Capacitors are an essential component in practically all electronic equipment. They are widely used for bypass, coupling, filtering and tuning of electronic circuits. To be useful, they must be characterized for value, voltage rating, temperature coefficient and leakage resistance. These tests are performed by the capacitor manufacturer, and may also be done by the end user.

This application focuses on the measurement of leakage resistance. This may be referred to as "IR" (Insulation Resistance) and is given in Megohm-microfarads. Or it may be expressed as a leakage current at a given voltage, usually the operating voltage.

Types of Capacitors

The leakage resistance (or IR) of a capacitor depends largely upon the dielectric used. The highest IR results from polymeric dielectrics, such as polycarbonate, polypropylene, and polytetrafluoroethylene. The IR may range from 10,000 Megohm-microfarads to as high as 100 Teraohm-microfarads.

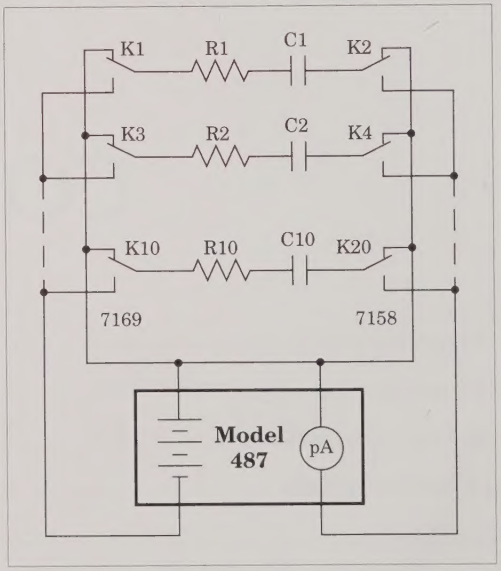

FIGURE 1

In a second class of dielectrics are various ceramics. These generally do not have quite as high an IR as the polymers but can be reasonably high. The range is 1,000 Megohm-microfarads to one Teraohm-microfarad.

Electrolytic capacitors have much lower IR, with a range of approximately one Megohm-microfarad to 10 Megohm-microfarads. Tantalum dielectric is usually much better than aluminum, but recent developments in processing of aluminum electrolytics have resulted in leakages comparable to tantalum.

Description

Since the leakage resistance of a capacitor is a function of the applied voltage, an ohmmeter is of little value in making the measurement. Instead, a fixed voltage is applied to the capacitor and the resulting leakage current is measured. Since the

leakage current will decay exponentially with time, it is usually necessary to apply the voltage for a known period of time (the "soak" time) before measuring the current.

Test Circuits

For statistical reasons a quantity of capacitors must be tested to give useful data. Since it is impractical to do this manually, some sort of automated test system must be used. The circuit in **Figure 1** shows such a system, with computer controlled switches to apply the test voltage to each capacitor in turn, and a second set of switches to connect each capacitor to the ammeter after a suitable soak period. This system will test up to ten capacitors, but can easily be expanded to any reasonable number.

If the leakage resistance is to be measured over an extended period, it may be possible to eliminate the voltage switches. With the normal form C, or transfer relay, each capacitor will see an open circuit briefly during switching. If this causes undesirable effects in the measurement, the circuit in **Figure 2** may be needed. Here two relays are used for each capacitor, one to complete the circuit directly to common, the other to connect the ammeter between the capacitor and common.

In this test system the functions of the voltage source and the picoammeter can be provided by the Keithley Model 487. This is a convenient instrument for this purpose since it can display either resistance or leakage current, and will source up to 500 VDC.

More complex test systems are possible, combining the leakage measurement with a capacitance measurement, dielectric absorption and other tests, if desired.

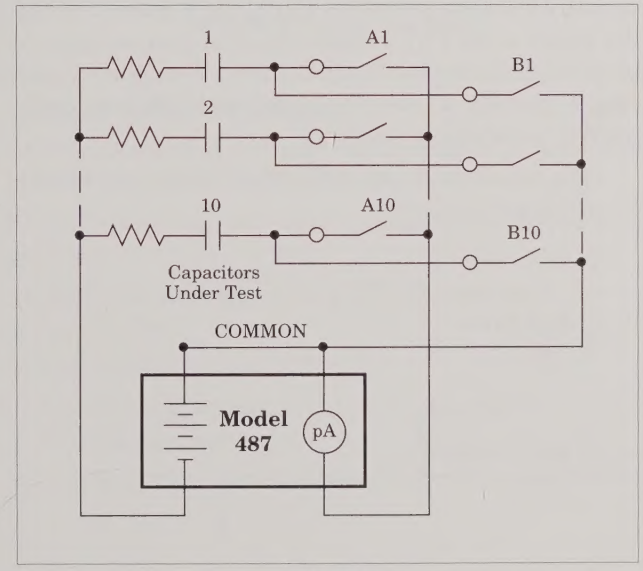

FIGURE 2

MEASURING CHARGE INJECTION OF ANALOG SWITCHES

Overview

FET analog switches can induce transients into signals during turn-on and turn-off periods caused by the control signal on the gate being capacitively coupled to the channel. This situation can be serious if the signal is at a high impedance level. For example, if a 30pC charge is injected into a capacitance of 0.01µF, the result is a 3mV step being developed across the device. Multiplexers can show similar behavior during input address transitions.

Figure 1 shows a typical waveform that might be seen at the output of analog switch, and **Figure 2** shows the model of an FET switch with gate-channel capacitance (C_{GC}). Each time the gate makes a sudden voltage step, a quantity of charge is transferred; this transfer is referred to as charge injection.

The amount of charge transferred to the channel can be calculated as follows:

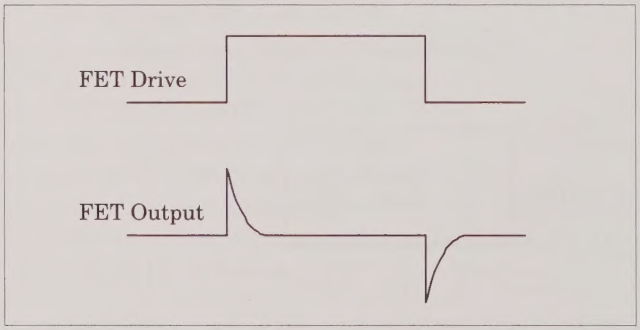

FIGURE 1: Typical Waveform of Analog Switch Output

$$Q = C_{GC}[V_G \text{ finish} - V_G \text{ start}]$$

Here, C_{GC} is the gate channel capacitance,V_G is t gate voltage and Q is charge.

There are several reasons why charge injection requires measurement.

- At times, C_{GC} is not known, and charge injection must be measured.
- The gate-channel capacitance is distributed over the length of the channel,which means that some of the charge is coupled back to the input of the switch. The amount of charge coupled back depends on the impedance of the signal source.
- C_{GC} may vary greatly among different FETs.
- C_{GC} varies with gate voltage.

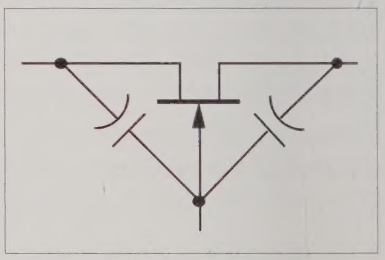

FIGURE 2: Model of GATE-CHANNEL Capacitance (C_{GC}) of a JFET

Description

Figure 3 shows a typical circuit configuration that can be used to measure charge injection. The Model 428 is used to amplify the charge injection signal, and it also provides the voltage bias. The output of the Model 428 is measured with a waveform recorder such as the Model 194A High Speed Voltmeter.

Keep the following points in mind when performing these tests:

1. Select a Model 428 gain that will not result in an overload. Keep in mind that, the lower the gain, the faster the settling time.
2. If noise becomes a problem, adjust the filter rise time so that any noise spikes are reduced.
3. The effects of device leakage can be eliminated by using the current suppression feature.
4. Measurement rate, number of samples, and trigger level on the Model 194A should be selected, so that the desired portion of the waveform is recorded.
5. The total charge transmitted in a circuit can be calculated by integrating the current in terms of time.

$$q = \int i\, dt$$

Here, i is the current in amperes, t is the time in seconds, and q is charge in coulombs. This calculation can be performed by a computer program, or by using the integral function of the Model 194A.

This same technique can be used to determine the capacitance (C_{GC}) of an unspecified FET. The value of C_{GC} can be determined as follows:

$$C_{GC} = Q / [V_G \text{ finish} - V_G \text{ start}]$$

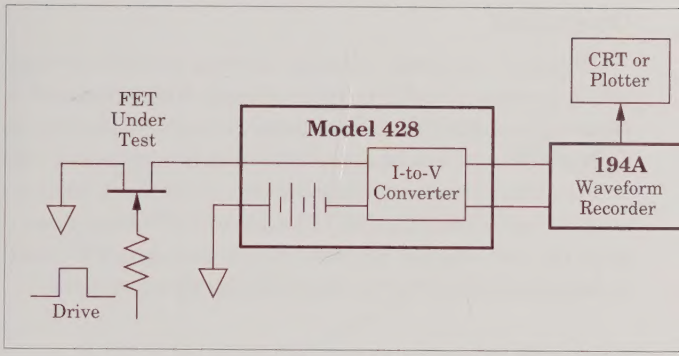

FIGURE 3: Typical Test Setup

Model 428 Advantages

- Output signal is a voltage that can easily be measured with a standard oscilloscope or waveform recorder.
- Built-in voltage bias source reduces total instrument count.
- IEEE-488 interface allows 100% test system automation.
- Low voltage burden (<200μV).
- Current suppression to eliminate the effects of leakage currents.
- Low pass filter reduces noise.

TRANSISTOR LEAKAGE CURRENT TESTS

Overview

Bipolar transistor leakage current values are very small, generally in the picoamp range. A picoammeter is required to make the current measurement. A shunt type ammeter would not be sensitive enough, and would also create an intolerable voltage burden. A feedback picoammeter, such as the Model 487 Picoammeter/Voltage Source with its low voltage burden, could measure the small leakage currents and not degrade the measurement.

Description

There are two leakage current measurements that are made on bipolar transistors. These measurements are commonly known as I_{CEO} (collector-emitter with base open) and I_{CBO} (collector-base with emmiter open). To measure the leakage currents, a voltage potential is placed across two terminals with the third terminal open (see **Figure 1**). The resulting current is measured. Although both parameters are known and the resistance could be calculated, the current vs. voltage data is generally plotted on a graph. The graph clearly shows the two parameters and the trend of the leakage current as voltage increases.

The Model 487 measures the leakage current and also sources the voltage. The voltage source would be set to one voltage and the Model 487 would take one reading. The voltage is then changed and the Model 487 takes another reading. This sequence continues until the entire test voltage range is completed. Note that the entire test can be accomplished using only one instrument. Also, with the internal memory of the Model 487, the current data can be stored as the test is progressing. At a later time, the data can be recalled to be plotted. Refer to **Figure 2** for a typical plot of the data.

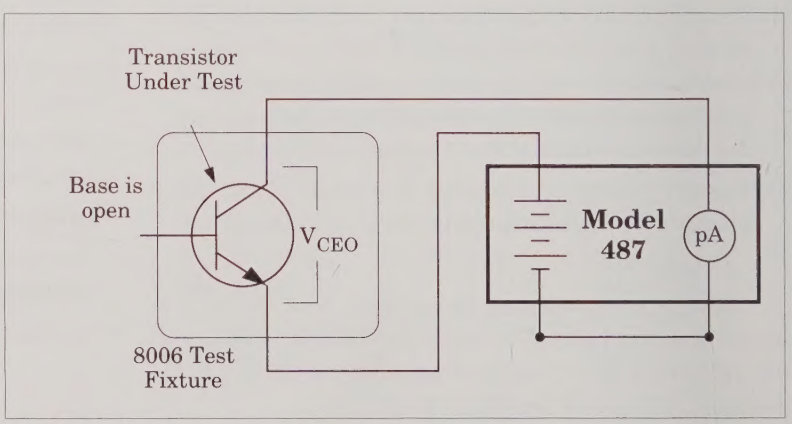

FIGURE 1: I_{CEO} Tests Configuration

With the aid of the computer, the test can be automated. A simple software algorithm will step the voltage in the Model 487 and the current can be measured and stored. When the test voltage range has been completed, the current data can be recalled to the computer and graphed on the CRT.

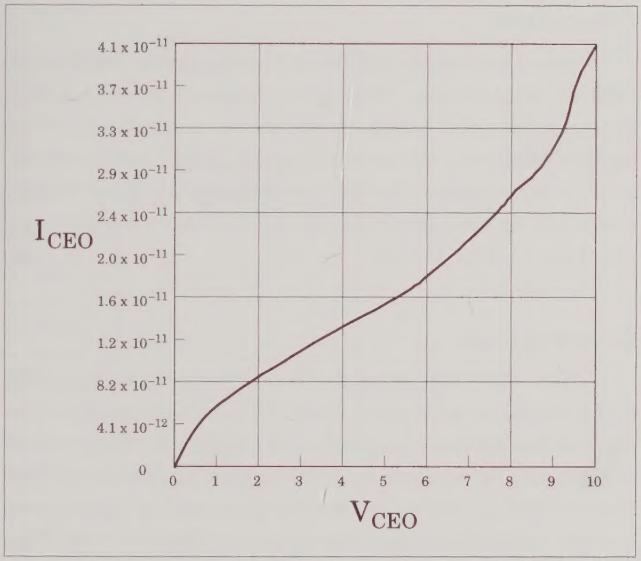

FIGURE 2: I_{CEO} vs. V_{CEO}

SELF-HEALING BREAKDOWN TESTS

Overview

Some insulators exhibit a phenomenon called self-healing breakdown. During an applied voltage ramp, these devices will break down one or more times. After each breakdown, the insulator will "heal" itself and appear to be a normal device (see **Figure 1**). Each breakdown will appear as a current pulse of short duration, as short as 10µsec. or less.

Description

Short duration breakdown current pulses are difficult to capture, especially when the precise voltage at the time of breakdown must also be captured. Such a test system can be realized by combining a precision current source (with a driven guard output) with a high-speed current amplifier and a dual-channel digitizer (see **Figure 2**).

The current source will charge C_R at a rate determined by the current output. C_R also limits the total short-term energy that can be present during a breakdown. The dual channel digitizer will monitor both the voltage on the device (via the driven guard) and the current through the device (via the current amplifier's analog output). In some cases, the voltage ramp may be approximated by using a linear staircase voltage sweep with very small step sizes.

For the current source, use a Model 237 Source-Measure Unit. This instrument can provide a precision current or a linear staircase voltage. Additionally, the Model 237 can provide a voltage clamp from 300µV to 1100V to prevent an over-voltage condition. For the high speed current amplifier, use a Model 428 Current Amplifier. This unit is capable of rise times as fast as 2µsec. with wide dynamic range. The dual-channel digitizer is a Model 194A equipped with the second channel option (Model 1944). This digitizer is capable of a 1µsec. sampling rate at 8-bit resolution or 10µsec. sampling at 16 bits. All of these instruments are programmable, allowing for easy computer analysis and graphing of data.

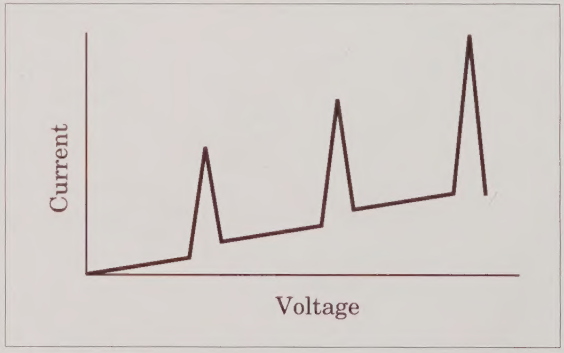

FIGURE 1: Breakdown Pulse Waveform

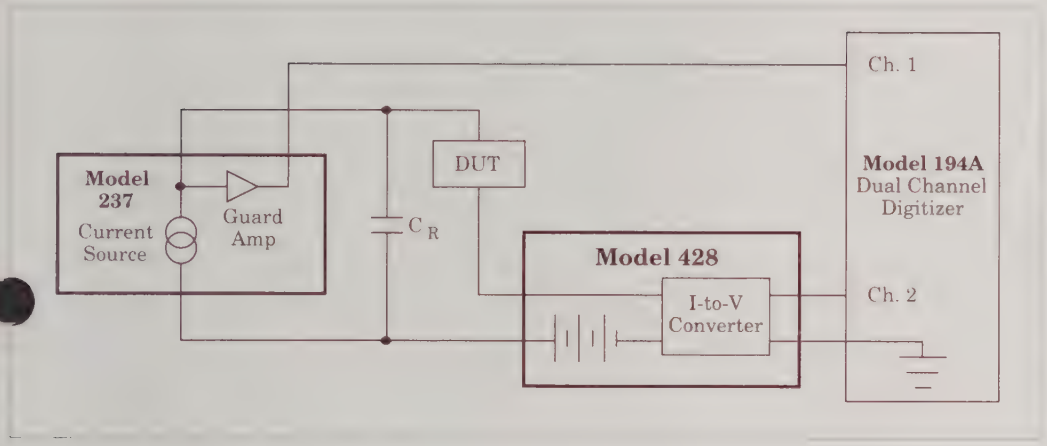

FIGURE 2: Typical Breakdown Test System

MEASURING RESISTIVITY

Overview

Measuring resistivity involves measuring resistance and then converting to resistivity (surface or volume) by factoring in the geometric considerations of the test sample.

To determine resistance, a known potential is applied to the test sample and the resulting current is measured. Resistance is then calculated using Ohm's Law (R=V/I). Samples can be tested with different potentials in order to determine any dependency of resistance on voltage.

The Model 487 Picoammeter/Voltage Source is an ideal instrument to measure resistance. The Model 487 is capable of measuring a wide range of currents very accurately and has a built in voltage source. The source is capable of up to 500 volts DC. This is the potential required in the ASTM standard D257 for measuring resistivity.

Description

Model 487 voltage source and picoammeter connections are shown in **Figures 1** and **2**. Voltage is applied and current is measured, providing the two factors required to calculate resistance. The V/I function of the Model 487 can be used to automatically calculate and display (in ohms) the resistance of the test sample.

The geometric considerations are then used to convert to resistivity. Volume resistivity is calculated as follows:

$$\rho = \frac{(22.9)\,(V)}{(T_C)\,(I)} \text{ ohm-centimeters}$$

where:

ρ is the volume resistivity of the sample

V is the applied voltage

Tc is the average thickness of the sample in centimeters

I is the measured current

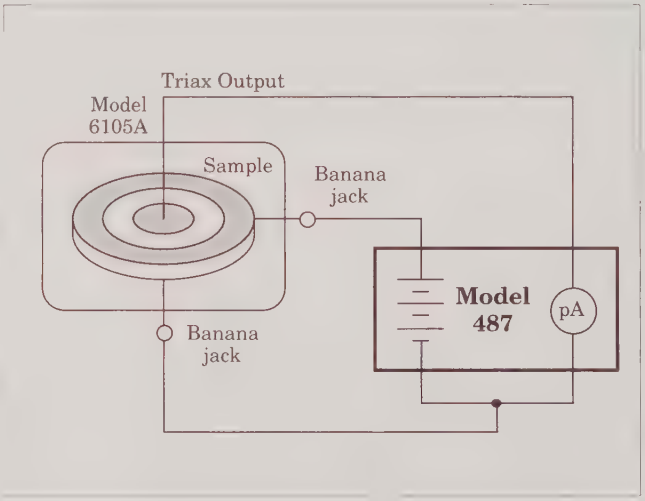

FIGURE 1: Surface Resistivity

Surface resistivity is calculated as follows:

$$\sigma = \frac{(53.4)\,(V)}{(I)} \text{ ohms}$$

where: σ is the surface resistivity of the sample

V is the applied voltage

I is the measured current

These calculations are derived from the physical dimensions of the Model 6105A resistivity chamber. The Model 6105A resistivity chamber is designed to allow convenient connection to the Model 487. The ammeter input of the Model 487 is connected to the Model 6105A current output (three lug triax). The Model 487 voltage source is connected to the voltage input terminals of the Model 6105A (banana jacks). Only the low current terminals of the test require shielded cables and connectors.

This resistivity system (Model 487 and Model 6105A) can test many different materials. Some of the materials include:

- Plastic - Measure resistivity of antistatic bags and packaging materials used to protect sensitive electronic components.
- Elastomers - Thermally conductive elastomers require high resistivity. Some are used as insulators between electronic components and heat sinks.
- Paper - Medium high resistivity to prevent static charge from developing on photocopier paper.

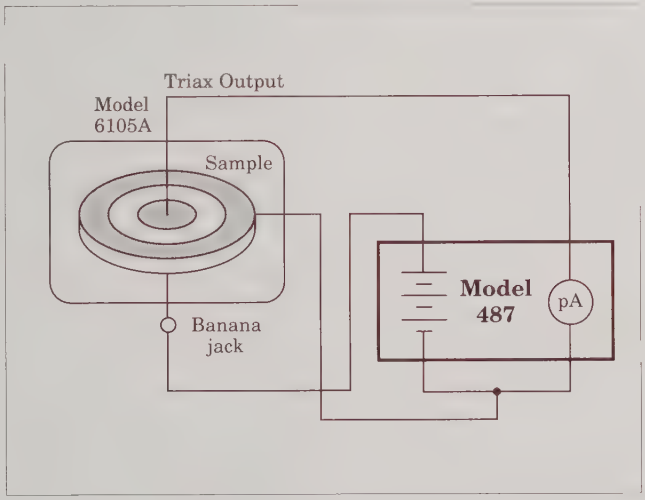

FIGURE 2: Volume Resistivity

INSULATION RESISTANCE TESTING OF PRINTED CIRCUIT BOARDS

Overview

Low insulation resistance (IR) of a printed circuit board (PCB) can considerably degrade the performance of the circuits on the board. Factors affecting the surface resistance of the board include the board material, coatings such as solder masking or conformal coatings, and the board cleanliness.

The measured resistance typically ranges from 10^7 ohms to 10^{16} ohms. Since this is beyond the range of most instruments, special measurement techniques must be used. The Model 487 Picoammeter/Voltage Source is ideal for this application.

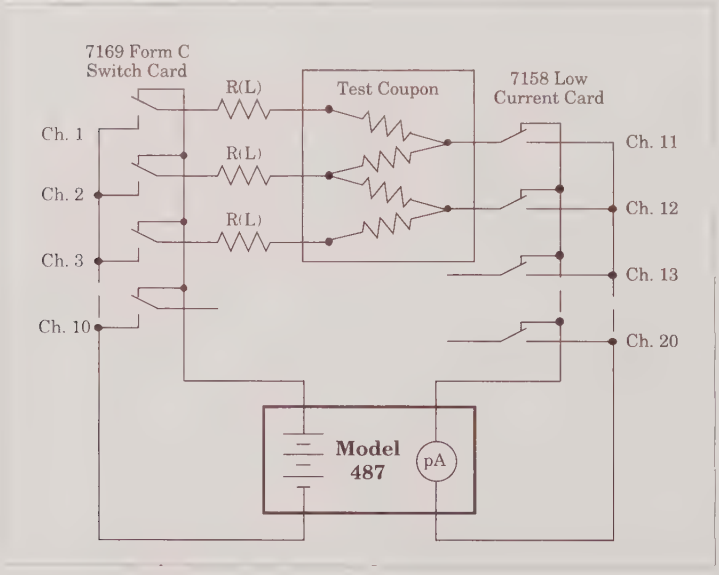

FIGURE 1: Circuit to Test a Single Test Pattern

Description

This application describes an automatic test system which polarizes and then measures the insulation resistance of a single "comb" test pattern. The most efficient way to control this test is to use a computer-based system using IEEE-488 bus controlled switches and measuring instruments. The required instruments and cabling are described in the following sections.

Instrumentation Requirements

The Model 487 applies the bias voltage, measures the leakage current and then calculates the resistance. The Model 487 can source voltages up to 500V. The Model 705 Scanner Mainframe is used to switch the picoammeter and the voltage source between test points. The voltage channels are switched using the Model 7169 Form C Switch Card, and the current channels are switched using the Model 7158 Low Current Scanner Card. The Model 7158 Card is designed to minimize offset current error which becomes a problem when measuring low current.

Testing a single coupon is illustrated in **Figure 1**. Each coupon can be thought of as four resistors in series, R1-2, R2-3, R3-4, and R4-5, so four measurements must be made. A single pattern requires three voltage channels and two current channels. Each of these scanner cards has ten channels so one of each card is required to test a single test pattern.

To measure the resistor R1-2, Channels 1 and 11 are closed. This will bias the resistor. After a specified soak time, the resulting current is measured. To measure the resistor R2-3, Channel 1 is opened, and Channel 2 is closed. Again the current is measured after the soak time. Immediately following this measurement, Channel 11 is opened and Channel 12 is closed to measure resistor R3-4 since this resistor is simultaneously biased with R2-3. To measure the last resistor, R4-5, Channel 2 is opened and Channel 3 is closed. After soaking the resistor, a reading is taken.

In **Figure 1**, the resistors, R(L), are current limiting resistors used to protect the switches and picoammeter from high voltage. The resistor value should be such that the voltage drop at the maximum current of interest will not affect measurement accuracy.

Cabling Requirements

To avoid noise currents, low noise coax cables should be used between the samples and the Model 7158 cards. Since the Model 7158 cards have BNC connectors, low noise cables terminated with male BNC connectors must be used. The parts recommended to build the cables are Keithley SC-9 Low Noise Cable and CS-44 Male BNC Connectors. A pre-assembled low noise coax cable is Model 4801 (4 ft.). The female BNC chassis mount connectors are part no. CS-249.

To adapt the Model 487's 3-lug triax input connector to the BNC output connector of the Model 7158, the Model 7078-TRX-BNC Triax-to-BNC Adapter is used. The Model 4801 Low Noise Coax Cable (one supplied with each 7158) connects the two together. The system cabling and connections are illustrated in **Figure 2**.

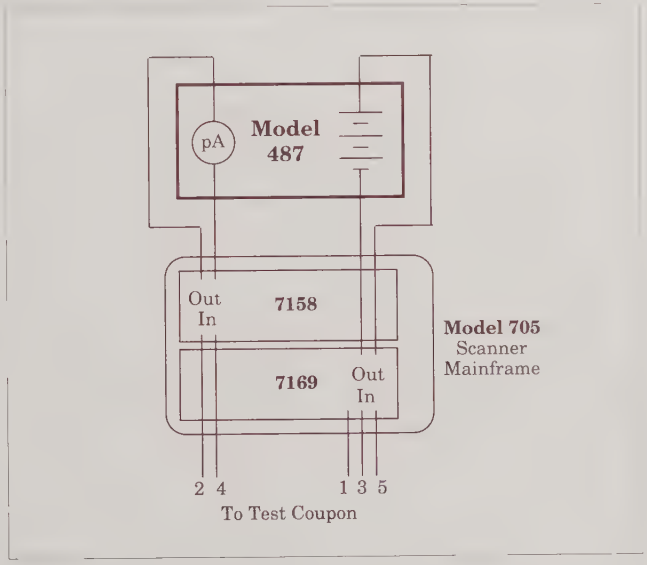

FIGURE 2: Cabling and Connections of the System

MEASURING THE OUTPUT NOISE OF A CURRENT SOURCE

Overview

Current noise is often a problem when sourcing or measuring low currents. Instruments have output noise specifications in several bandwidths informing the user of its limitations. These specifications can be stated in rms, peak-to-peak or peak. Measuring the noise output of a current source is a difficult task. In addition to the problem of selecting a different resistor for each range, each resistor must be well shielded. Special cables must be used to keep external noise out, a time consuming and frustrating task.

Description

The Model 428 Current Amplifier is ideal for testing output noise of a current source. The unit is capable of amplifying currents with bandwidths from DC to 150kHz. Using the Model 428 in conjunction with a Model 194A High Speed Voltmeter results in greatly simplified test procedures. Using the Model 194A, key aspects of the waveform can be quickly derived. The sampling rate of the Model 194A can be as fast as 1μsec. with up to 65,535 samples taken in one reading, allowing ample data for display of noise in specified units (rms, peak-to-peak, peak, etc.).

1. Connect all instruments as shown in **Figure 1**. The current source of the UUT is connected to the input of the Model 428, and the output of the Model 428 is connected to the input of the Model 194A.
2. Select the range to be tested on the UUT.
3. Select the bandwidth on the Model 428 by the following relationship:

   Bandwidth = 0.35 / Rise time
4. Approximate the noise output, and set the range on the Model 428 accordingly (i.e., if 1mA is being tested and the spec is 1ppm p-p, the Model 428 should be set to 1×10^{8}V/A gain to measure 1nA p-p noise).
5. Select the rate and number of samples desired on the Model 194A.
6. Source zero current from the UUT on the selected range.

7. Select the type of measurement analysis (rms, peak-to-peak, peak, etc.) on the Model 194A.
8. Adjust both the Model 194A and the Model 428 to provide the best readings.
9. Record noise by:

rrent Noise = Model 194A reading / gain setting of the 428.

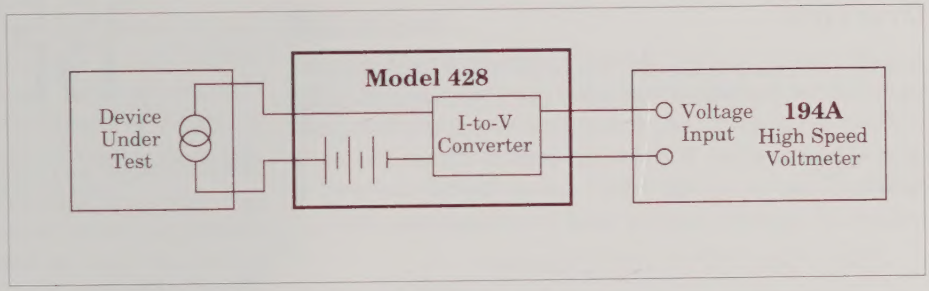

FIGURE 1: Current Noise Measurement

Alternate Methods

The output of the Model 428 could also be fed into an oscilloscope for visual display of the noise. A chart recorder could also be used on the output of the Model 428 to record noise over time.

Model 428 Advantages

- Low cost
- Fast, accurate set-up
- IEEE-488 bus programmable

MEASURING POWER SPECTRAL DENSITY

Overview

The power spectral density (PSD) of a time domain signal shows the signal frequency power and content. The PSD is used by scientists and engineers to analyze experimental test results. If the time domain signal has been digitized (as is typical when using digital meters), a numerical method must be used to compute the PSD:

$$PSD_k = 2 \times (T_s/2^n) \times |FFT_k(data)|^2$$

where PSD is the power at normalized frequency k.

FFT_k(data) is the fast fourier transform of the 2^n digitized "data" points at normalized frequency k.

T_s is the period between data samples, n is the number of samples taken (must be a power of 2 for the FFT algorithm).

k is is an integer from 0 to 2^{n-1} representing a normalized frequency ($2 \times k/T_s$ is the actual frequency at point k).

Each PSD frequency point is computed by squaring the magnitude of the complex FFT values and scaling by twice the sample period divided by the number of data points. By plotting these 2^{n-1} PSD points versus k, the signal's power spectrum is shown.

The FFT can be computed by writing a software program or by using one of the many existing mathematics programs (such as ASYST, ASYSTANT, MATLAB, MATHCAD, or any signal processing/data analysis package) that have built-in FFT functions.

Description

One application requiring PSD analysis is measuring the low frequency current noise spectrum of a component. The Model 487 Picoammeter/Voltage Source and the ASYSTANT data analysis package can be used together to produce the required PSD.

The setup for this test is shown in **Figure 1**. The Model 487 is configured to source voltage to the DUT and measure the subsequent current. Use the DATA STORE of the Model 487 to acquire 512 readings at a 50msec. trigger interval.

When the DATA STORE operation is complete, use ASYSTANT to transfer the Model 487 buffer data over the IEEE 488 bus.

With the data in the ASYSTANT program, perform the PSD equation using the built in FFT and magnitude functions. (A continuous or periodic waveform in the acquired data will need to be "window"-ed prior to performing the FFT. A window function is provided in ASYS-

TANT for this purpose.) The values for T_s and 2^n are 50msec. and 512 respectively. Note that the 487 DATA STORE buffer size was set at a power of two for convenience in performing the FFT function. Otherwise, the data would have to be manipulated (truncated or padded with zeroes) to force its size to be a power of two.

With the PSD data now computed, it may be plotted on the computer screen and printed through the use of ASYSTANT.

Reference

Random Data: Analysis and Measurement Procedures; Bendat, Piersol; Wiley-Interscience.

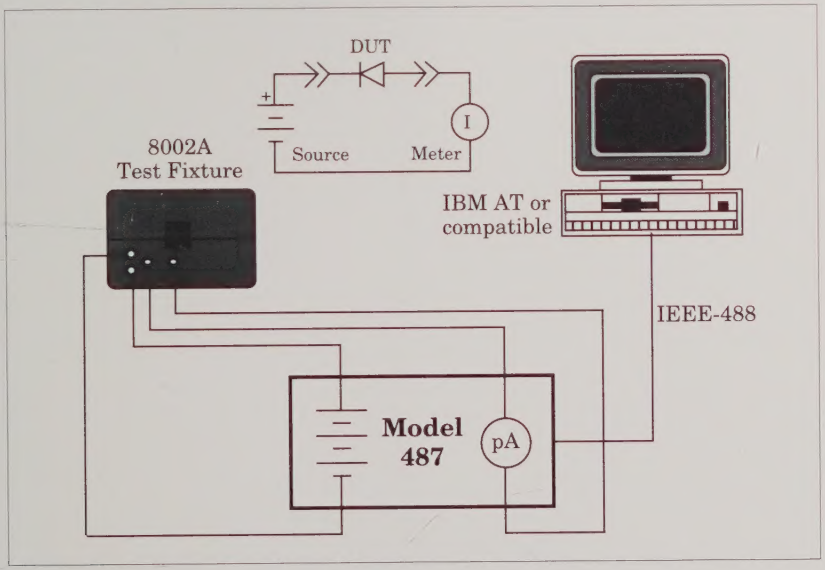

FIGURE 1

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